An Introduction to Crystal Filters

PART I

By HAMISH V. BELL, B.Sc. (G3MAZ)*

WITH the ever increasing popularity of the single sideband (A3a) mode of transmission, attention is being focused on what, for the amateur, are two unusual types of networks. One is the resistor-capacitor network which will act as a 90° phase shifting device over a range of audio frequencies, and the other is the crystal filter. It is the intention of this article to review the latter in a simple manner, and so possibly elucidate some of its mysteries.

It is well known that a quartz plate when mounted between two metal electrodes and excited electrically will vibrate mechanically at a certain fixed frequency. This frequency is dependent upon the size and shape of the plate, and the position in the parent crystal from which it was cut. Although this is a mechanical vibration the effect can be represented near resonance by an equivalent electrical circuit as shown in Fig. 1.

The capacitance *Co* is the capacitance of the metal electrodes with a quartz dielectric, and includes the effect of any air gap between the electrodes and the crystal. The components *L*, *C* and *R* are governed by the cut and the dimensions of the quartz plate. Typical values of these components for an 80 kc/s crystal might be as follows:

$L = 39{\cdot}7$ H $R = 900$ ohms
$C = 0{\cdot}1$ pF $Co = 17$ pF

$$Q = \frac{\omega L}{R} = 22{,}000$$

This value of Q is much higher than any that can be obtained using inductors and capacitors with the result that

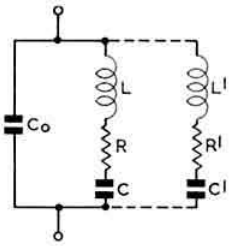


Fig. 1. Equivalent electrical circuit of crystal near resonance. Effect of spurious frequencies shown by dashed lines.

filters employing crystals are capable of high attenuations outside the passband with rapid transitions from passband to stopband.

The ratio $\frac{Co}{C}$ imposes a fundamental limitation upon the characteristics of the crystal and thus of any filter in which it is used. This ratio depends upon various electrical and mechanical constants for the quartz and has a theoretical minimum value of 140 with stray capacity increasing this figure. In practice, however, for low frequency crystals it is found that a smaller value is realizable, usually around 125 [1].

The electrical circuit of Fig. 1 will have two significant frequencies. At these frequencies, the combination will appear either as a series tuned circuit or as a parallel tuned circuit, and at other frequencies will have intermediate values of impedance. Generally the crystal resistance can be neglected since the effective Q of the crystal is high and so it is usual to plot reactance—frequency diagrams rather than impedance graphs when considering a filter response. The graph of reactance against frequency for a single crystal is shown in Fig. 2 and it is seen that as the frequency is increased a series resonance occurs (zero reactance) followed by a parallel resonance (infinite reactance). These frequencies are respectively the resonant frequency (*fr*) and the anti-resonant frequency (*fa*) of the crystal unit and are most important in the consideration of crystal filters.

Another way of expressing these significant points is to term points of zero reactance (such as *fr*) as ZEROS and points

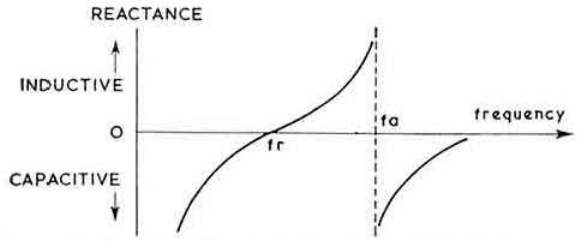
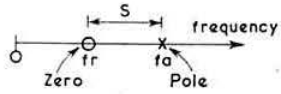


Fig. 2. Graph of reactance against frequency for crystal.

of infinite reactance (such as *fa*) as POLES. The pole-zero plot of the crystal equivalent circuit will then look like Fig. 3.

It can be shown that the pole-zero spacing, S, is related to the ratio $\frac{Co}{C}$ by the expression $S = \frac{fr}{2}\frac{C}{Co}$. From this it is obvious that any capacity added in parallel or series with

Fig. 3. Pole-zero plot of crystal.



the crystal will decrease the spacing between the resonant and the anti-resonant frequencies.

If inductance is placed in series or parallel with a crystal the opposite effect occurs. For the series case (Fig. 4), it is seen that the crystal pole remains fixed while its zero is lowered in frequency. A further zero or series resonance is also introduced higher in frequency than the crystal anti-resonant frequency. In Fig. 5 the parallel case is illustrated and here the crystal zero remains fixed while the pole is moved higher than its original frequency. As in the series case a further significant frequency is introduced, a pole, lower in frequency than the crystal zero.

Besides the main responses at *fr* and *fa*, other responses may be found. These spurious responses are higher in frequency than the parallel resonant frequency and are due to mechanical coupling within the crystal. They may be represented electrically by further series circuits (shown by

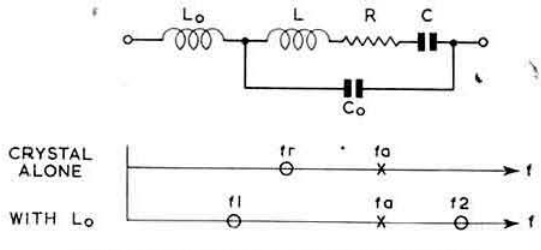


Fig. 4. Effect of inductance in series with crystal.

* *152 Kingsway, Widnes, Lancs.*

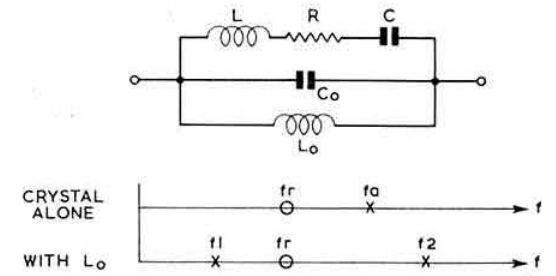


Fig. 5. Effect of inductance in parallel with crystal.

dashed lines in Fig. 1) placed in parallel with the main circuit, and their effect will be referred to later.

Having reviewed the electrical characteristics of the crystal unit and seen how these characteristics may be modified by suitably connecting inductors and capacitors, the use of these elements in filters can now be considered.

Filter Configurations

The basic filter configuration may be considered to be the lattice, or bridge circuit, since other configurations may be transformed into the lattice form by means of mathematical processes.

Crystal Gate

The simplest form of lattice filter and the one which will be used to introduce the method of finding the passband and

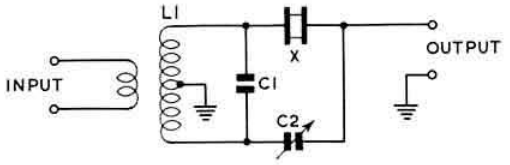


Fig. 6. Crystal gate or one-crystal lattice filter.

frequencies of infinite attenuation, is the so-called " crystal gate." This form of filter has been used for many years in communication receivers as a means of increasing the i.f. selectivity for c.w. and also to a certain extent for telephony as well.

The circuit is shown in Fig. 6 and is, to all intents and purposes, a bridge circuit. When the voltage due to the crystal arm is equal and opposite in polarity to the voltage due to the capacitor arm, there will be a balance and no output will be obtained. This infers that at some frequency the reactance of the crystal must be capacitive and equal to the reactance of C2. At this frequency on the attenuation-frequency curve there will appear a point of infinite attenuation. If on the other hand, the crystal reactance is inductive and numerically equal to the reactance of the capacitor, then the output voltage will be a maximum since the voltages of the two arms will add together. At other points, the outputs will vary between these extremes.

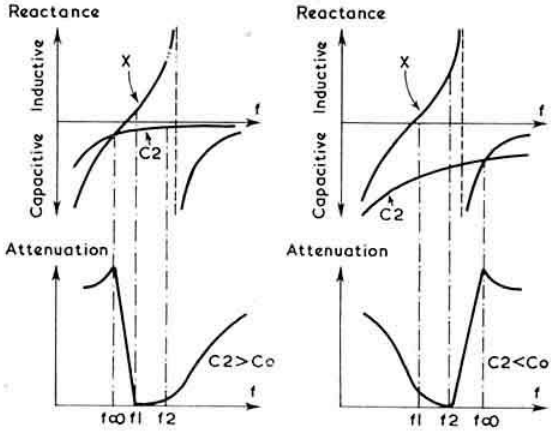


Fig. 7. Reactance-frequency and attenuation-frequency graphs for crystal-gate filter.

The reactance curves for the crystal and for the capacitor are shown in Fig. 7. Also included in this diagram are the appropriate attenuation-frequency curves for values of C2 greater than and less than *Co*, the crystal capacitance.

It is seen that the passband extends from a frequency *f1*, higher than the crystal resonant frequency to *f2*, a frequency just less than its anti-resonant frequency, i.e. it lies between the highest and lowest significant frequencies. The passband is only a matter of a few hundred cycles in width and will not be flat. The frequency of infinite attenuation, $f\infty$, is below the passband when C2 is greater than *Co* and higher than the passband when C2 is less than *Co*. The capacitor C2 is the familiar phasing control which can be used to reject an interfering carrier near to the desired signal by adjusting the frequency of infinite attenuation to coincide with the interfering signal.

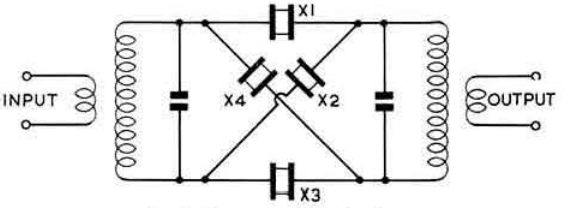


Fig. 8. Four-crystal lattice filter.

The main disadvantages of this simple form of filter are that the passband is not very wide, and also the frequency of infinite attenuation can only be placed on one side of the passband at one time. This results in the skirt on the other side sloping rather badly.

Four-Crystal Lattice

The form of lattice usually favoured in commercial practice employs four crystals as shown in Fig. 8. The coils which terminate the filter can be shown mathematically to be effectively in parallel with the crystals, thus spreading the crystal pole and zero frequencies and introducing a further pole as was indicated in Fig. 5.

If the poles and zeros produced by crystal X1 are coincident with those of crystal X3 and the poles and zeros of X2 are coincident with those of X4 then only the reactance diagram of X1 and X2 need be considered to obtain the attenuation characteristic. In the diagram of Fig. 9, the reactance of the series crystal, X1, is represented by a solid line and the reactance of X2 by a dashed line. Crystal X2 has a resonant frequency higher than X1 by the amount of the pole-zero separation. In this way one of the poles of X2 coincides with the zero of X1 and one of the poles of X1 coincides with the zero of X2. A passband then exists between the lowest and highest significant frequencies, actually lying just within these frequencies. The bandwidth can be made about 3 kc/s at frequencies up to 500 kc/s with this circuit. Two frequencies of infinite attenuation are produced, and these can be controlled to some extent by a small capacitor across one of the higher frequency crystals, as also can the flatness of the passband. However, all is not as simple as it seems with this filter. One of the main requirements is that the

crystal frequencies shall be precisely adjusted so that the zeros of the pair of series crystals are coincident with each other and with the poles of the shunt crystals. If the crystals are not closely matched, the passband will be uneven and also stopbands may appear within the passband. These factors all add up to a circuit which is not the easiest to

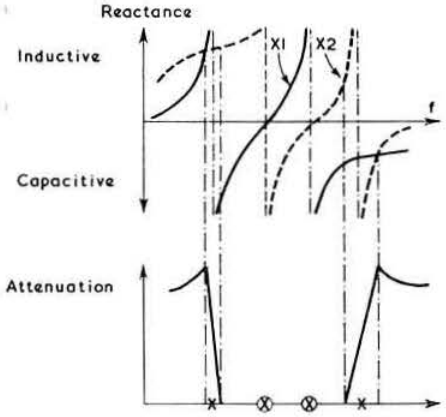


Fig. 9. Four-crystal lattice filter reactance-frequency and attentuation-frequency graphs.

adjust. In commercial practice some of the difficulties of matching are overcome by plating two sets of electrodes on a single quartz plate; the amateur has to turn to other circuit configurations to achieve the same ends.

Two-Crystal Lattice

A suitable circuit is shown in Fig. 10 and is generally called the half lattice filter, although in fact it is the unbalanced equivalent of the four-crystal lattice. The crystals X1 and X2 are the same as the series and shunt crystals in Fig. 8, and have the same frequency relationship. The reactance and attenuation diagrams are the same as for the four-crystal lattice. A capacitor C2 is placed across the higher frequency crystal to enable its pole-zero spacing to be altered slightly. In this way the crystals can be matched to give a flat passband with steep sides and a frequency of infinite attenuation above and below the passband. The circuit L1 C1 is tuned to the mid-band frequency, as also is L2 C3. For best results the input circuit should be as shown, i.e. with the inductor L1 physically centre-tapped, but this is generally difficult to arrange because of the relatively low frequencies at which these filters are used. The alternative (Fig. 11) is to artificially centre-tap by means of two capacitors in series, connected in place of C1. These capacitors are each twice the value of C1 and should be high quality silver mica types in order that the filter characteristic will not be greatly affected by temperature.

This method is usually satisfactory but could be contributory to some attentuation in the passband, since there is

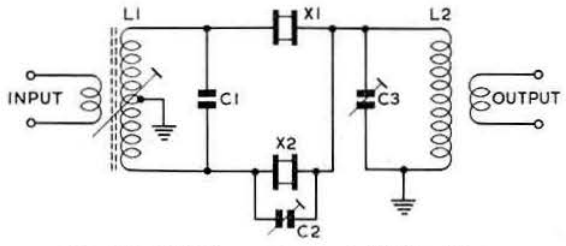


Fig. 10. Half-lattice or two-crystal lattice filter.

a relatively high current demand when one crystal is series resonant. This will tend to unbalance the input circuit which is high impedance and so balanced for voltage only.

Using surplus FT241 type crystals, the input impedance of this filter configuration will be about 250 K ohms for a one per cent bandwidth at the frequencies employed, around 300 to 500 kc/s. This frequency range allows most normal i.f. transformers to be used as input matching devices and pole-zero spreading inductors when modified as in Fig. 11. The comments in the next section on dissipation should be borne in mind when assessing the suitability of any particular transformer, since several factors influence the choice.

The crystals employed should be measured and adjusted so that the relevant poles and zeros are on the same frequency, within a few cycles. Care should also be taken to ensure that all the crystals show approximately the same activity. This is an indication of their Q and since the frequencies of the crystals in a half-lattice filter differ by only 1·5 kc/s or so, it is also an indication of their series resistance. If desired, the series resistance can be measured directly as described later in the measurements section. The series resistances and hence the Q values are only important in that a large difference between crystals will affect the transmission through the filter and, to a lesser extent, the slope of the skirts of the passband. However these are not very critical parameters and differences in series resistance of up to 30 per cent should provide acceptable results.

The half-lattice filter has been very popular for some time, since the use of i.f. transformers for input and output coupling devices and the availability of suitable crystals simplifies construction. It is also quite tolerant of circuit constants so that by appropriate juggling of the transformer tuning slugs

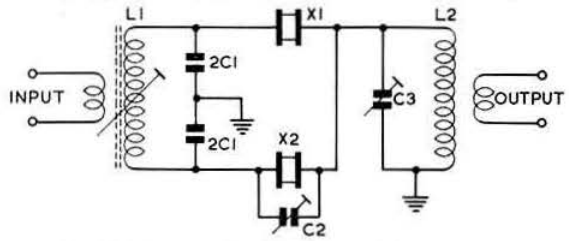


Fig. 11. Two-crystal lattice with capacitive centre-tap.

and the capacitor in shunt with the high frequency crystal it is possible to achieve attenuations greater than 35db over the stopbands with very little dip in the passband.

Where a higher attenuation in the stopband is required, two or more sections may be placed in cascade so that their effects will be additive. This procedure allows less critical adjustment of the filter, although even so it must be laid out carefully if capacitive coupling round the filter is to be avoided and high attenuations achieved.

Dissipation and Termination

Since the properties of these filters depend upon the extremely high Q factors of quartz crystals it may be wondered what effect the Q of the inductors used in the filter has on the overall characteristics. Owing to their high Q factors, crystals can be considered dissipation-less compared with coils, and so the actual filter without terminations does not introduce loss within the passband. Any inductors in series or parallel with a crystal can be transformed mathematically to become part of the terminations; thus this concept of a dissipationless filter is true for any filter. This treatment leads to the view that the attenuation outside the passband is mainly dependent upon the filter and any loss within the passband is due to the terminations.

The loss within the passband can be of two types. The

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Two further amateur band ranges are available with crystals providing coverage for the remaining portions of the 28 to 29·7 Mc/s band, whilst five universal ranges of 600 kc/s each may be selected between 3 and 30 Mc/s by the choice of suitable crystals. This provides a total of twelve 600 kc/s bands which may be selected from the front panel. Internal spurious responses, always a problem in this type of receiver, are held to a level which is less than an equivalent 1 μV signal. The dial calibration is marked at intervals of 10 kc/s, with 1 kc/s vernier dial divisions on the rim of the tuning knob, both of these being adjustable for calibration purposes. The S meter, which is operative on all modes, forms part of a bridge circuit in the anodes of the r.f. and i.f. amplifiers. However, after the S meter had been calibrated in accordance with the instruction manual it was found that only a local signal would produce an S9 reading.

Operation

The receiver has been used for the reception of all modes of transmission and naturally the 3·6 kc/s bandwidth position provides the most faithful reproduction of a.m. signals, whilst the 2·1 kc/s position is optimum for s.s.b. The 500 c/s bandwidth enables c.w. signals to be read through heavy QRM, and when the *Q* Multiplier is used this can provide true single signal reception. At any position of the bandwidth switch the passband tuning control allows selection of upper or lower sideband without readjustment of the main tuning control. Sideband signals are as easy to tune as their a.m. counterparts, and in the event of heavy QRM the 500 c/s bandwidth is usable although obviously speech quality suffers. The adjacent channel selectivity is steep sided and approaches that provided by mechanical filters whilst the passbands are continuously movable above and below the fixed b.f.o. frequency of 50 kc/s. The bandwidth at 60db down on the three selectivity positions is 2·75 kc/s, 7·5 kc/s, and 10·5 kc/s respectively.

It is desirable that a receiver capable of high selectivity should also have good frequency stability and in this respect the Model 2-B is second to none. The manufacturers claim a warm-up drift of less than 400 c/s, and a shift of less than 100 cycles after this initial period; experience has given no grounds for argument with these figures, which are the result of the use of a crystal controlled first oscillator and a carefully designed low frequency variable escillator.

A review of this nature can only deal briefly with the salient points of the equipment used and many details must be left unmentioned, but it should be said that the feel of the main tuning control, which is coupled by a cord drive to the dial mechanism, left something to be desired and a geared flywheel arrangement would be preferred. The mains transformer in the receiver is designed for 60 c/s operation which probably accounts for a large proportion of the heat radiated from this component. However, during an extended period of operation the Model 2-B gave every satisfaction and is highly recommended as a communications receiver of outstanding performance. The latter, in the experience of the writer, has been excelled only by a receiver the cost of which was roughly three times that of the Drake product.

The Model 2-B receiver reviewed was supplied by K.W. Electronics Ltd. of Vanguard Works, Heath Street, Dartford, Kent, and costs £138, including the crystal calibrator and loudspeaker/*Q* Multiplier.

The G4ZU FB-5 Aerial

THE type of bead required for the G4ZU FB-5 aerial described in *Technical Topics* on page 283 of the December issue of the BULLETIN is Mullard B4 pattern FX1308 and not FX1300 as mentioned.

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first is frequency sensitive and gives rise to an uneven passband; the second provides a constant loss and can be considered as a purely resistive effect. This latter loss is of little consequence, since it can be made good in any amplifier associated with the filter, by merely increasing its gain.

The former type, however, is a little more difficult to eliminate as it usually results in a deep dip in the middle of the passband. This effect can be due to two causes, the first being that the pole of the l.f. crystal does not coincide with the zero of the h.f. crystal. Any dip due to this can only be fully eliminated by ensuring that these two frequencies do coincide. The second cause arises when the dynamic impedance of the input tuned circuit at resonance is comparable with the input impedance of the filter, thus lowering the effective impedance across which the signal is developed. If the dip becomes more than about 6db below the maximum response of the filter, the distortion of signals passed through the filter is most noticeable. By using inductors having relatively high *Q* factors it is possible to adjust the terminations so that the dip in the passband is well below this figure and thus a reasonable flat response may be obtained. A coil of 1·8mH having a *Q* value of 50 or greater would enable this state of affairs to be achieved at 465 kc/s with the half-lattice filter described. However, since the dynamic impedance of the coil depends upon the frequency and the inductance as well as the *Q* factor, it is not possible to generalise. A far better guide to the values required in any particular case can be obtained by considering the dynamic impedance of the tuned circuit and comparing it with the filter input impedance in the passband.

If Z_d is the dynamic impedance, then $Z_d = L/CR$ where L, C and R relate to the tuned circuit, and $Q = \frac{L}{R}\omega$ Hence $Z_d = 2\pi f_o QL$ where f_o is the resonant frequency of the tuned circuit. Now for least dip in the passband the dynamic impedance should be several times greater than the filter input impedance, but if this is not possible, an absolute limit for satisfactory operation can be considered to be when Z_d equals the filter input impedance.

A Three Band Crystal Controlled Converter

(Continued from page 335)

amount of oscillator output on any band may be made by altering the value of h.t. dropping resistor to the coil concerned.

Once the crystal oscillator is functioning satisfactory, L1 and L2 should be adjusted so that signals on all three bands may be peaked with the 100 pF tuning capacitors. The 14 Mc/s band should resonate near the maximum capacity of these capacitors and 28 Mc/s near minimum capacity. Once set up for a given band no further adjustment should be necessary, all tuning being carried out on the main receiver.

Results

The converter has been in regular use by the writer for five years working into a CR100. The combination gives excellent results from the stability point of view and the sensitivity appears to be very good. The converter has also been used with other receivers during recent National Field Days with complete reliability and has earned the approval of all who have used it.

Since this article was written it has been pointed out that under certain conditions harmonics from the crystal oscillator may cause TVI. Reducing the HT voltage to the circuit concerned by increasing the value of the dropping resistance together with further decoupling of the HT line will effect a cure.

An Introduction to Crystal Filters

PART 2—H.F. Filters

By HAMISH V. BELL, B.Sc. (G3MAZ)*

IN Part 1 the discussion was related to crystal filters in the low-frequency spectrum below 1 Mc/s since these are the type most generally used and about which the most is known. However, it has been shown [2] that the selectivity of a simple bandpass filter is dependent only upon the pass-band width and the position of the frequency of infinite attentuation relative to the cut-off frequency. In other words, it is not, in theory, dependent upon the centre frequency of the filter.

"In theory," there of course lies the difficulty! There is a limitation in practice in the value of *Q* factor which is obtainable and in the stability of the crystal unit. Nevertheless, there is a great deal of incentive to devise a workable high frequency filter, since its use would be advantageous both in receivers and s.s.b. transmitters. Fewer frequency conversions would be required and high selectivity could be achieved so that the receiver, or transmitter, would be less liable to generate spurious signals.

Assuming there is no limitation on the mid-frequency of a filter, any configuration used at the lower frequencies can be used as a high frequency filter. However the more stringent requirements as regards stability and *Q* factor usually result in designs which are difficult to achieve practically.

To make a four-crystal lattice filter for frequencies of the order of 5 Mc/s with access only to surplus crystals would be virtually an impossibility and so some other approach must be found.

One such approach is that suggested by W3TLN (*QST*, January, 1959) based upon an article by Kosowsky in the

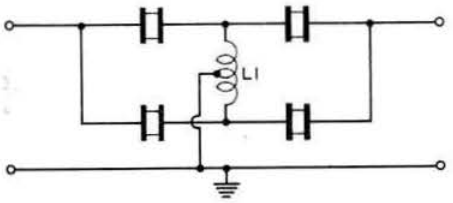

Fig. 12. "Back to back" connection for high frequency filter suggested by W3TLN.

Proc.I.R.E. (February, 1958). This employs a pair of two-crystal lattices connected "back to back" as in Fig. 12. The coil L1 serves as a load for each section and according to W3TLN is apparently not critical as regards inductance, although in common with any inductor associated with a filter, it should have as high a *Q* as is possible. For details regarding the construction of a filter of this type the article by W3TLN should be consulted; instructions for shifting the crystal frequencies are also given.

Spurious Responses

At this point, a short digression is permissible to consider the effect of spurious crystal responses on the filter characteristic. It was mentioned earlier that spurious responses could occur in crystals and could be represented by another series inductor and capacitor in parallel with the components giving the main resonance.

The crystals used for the low frequency filters are fortunately free from spurious responses, due to the particular cut used, and so this factor is not important. This is not the case with crystals designed for higher frequencies and indeed some of the spurious responses can be as little as 3db below the main response. The spurious frequencies may be moved within certain limits during manufacture but even in a well-designed crystal cannot be eliminated entirely. The final placing is dependent upon the cut and the physical properties of the crystal. Methods used to reduce spurious responses include special grinding techniques and also the plating of only part of the crystal on each face, the latter having the secondary effect of reducing the parallel capacitance. Such measures, of course, are not generally available to the amateur but nevertheless it is interesting to consider commercial practice.

Suitable Crystals for H.F. Filters

Coming now to crystals which are available cheaply to the amateur, the obvious choice is the FT243. It is not, however,

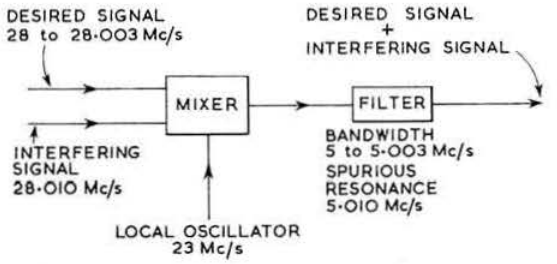

Fig. 13. Effect of spurious responses in filter used for reception.

just a matter of selecting a crystal marked with the required frequency and hoping that it will fit the bill. Possibly the figures in Table 1, relating to one crystal of this type, will help to impress the point. Measurements were made on several crystals, using accurate frequency determining equipment, and these figures are representative of the others. It is seen that there are three spurious responses of which the first is the one most likely to cause trouble.

In order to reduce the effect of these responses, several filter sections should be used in cascade since it is unlikely that two spurious responses will occur at the same frequency. The result will be a lower value of attentuation at the spurious resonance frequencies but no actual passband will be formed. For filters used for transmitting, this is quite satisfactory, since the audio response can be shaped to cut off sharply at 300 and 3300 c/s. There is thus very little signal passed to the filter at the spurious resonance frequencies. For reception,

TABLE 1

Measurements on FT243 Crystal

Marked frequency	6850 kc/s
Measured resonant frequency	6848·299 kc/s
Measured antiresonant frequency	6849·935 kc/s
Pole-zero spacing	1·636 kc/s

Spurious Responses

Higher than antiresonant frequency	Level relative to main response
5·024 kc/s	−12db
12·658 kc/s	−5db
13·759 kc/s	−11db

Equivalent series resistance at resonance ≃ 250 ohms
Effective parallel capacity = 11·1 pF

* *152 Kingsway, Widnes, Lancs.*

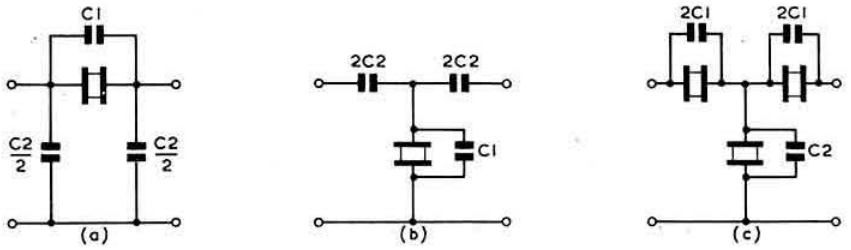

Fig. 14. Basic sections of ladder filters (a) Lowpass, (b) Highpass, (c) Bandpass.

however, the situation is somewhat different, since a signal at the input can beat with the local oscillator to produce the spurious resonance frequency, and will be passed to the detector along with the desired signal. This is illustrated in Fig. 13. Generally the attentuation will be greater for the interfering signal than for the desired signal, but their relative strengths may counteract this.

Ladder Filters

A form of filter not generally employed at low frequencies is the ladder type, three forms of which are illustrated in Fig. 14. The reason for its lack of use is the low percentage bandwith available since the filters are comprised of crystals and capacitors only. At high frequencies, however, although the percentage bandwidth is the same, the actual bandwidth in cycles per second is sufficient for an i.f. amplifier. With the crystals available, this configuration does look as though it may be a possible approach to high frequency crystal filters.

Owing to the large number of spurious responses, it is much better to employ only one crystal in each section and put a number of sections in series. For s.s.b. transmitters therefore it is only necessary to connect either a number of lowpass sections or a number of highpass sections in series to select the required sideband, the audio response being tailored to provide the necessary 3 kc/s bandwidth. For a receiver i.f. amplifier it would be necessary to have a bandpass characteristic formed by putting a number of highpass filter sections after a number of lowpass sections. Alternatively a bandpass section could be used but this would be more critical to adjust and the choice of rejection frequencies would be limited. The suppression of spurious frequencies would also be reduced.

Taking the circuits of Fig. 14, it is seen that no d.c. path exists between input and output and so the response will fall off at low frequencies. The bandwidth depends upon the ratio $\frac{C1 + C_o}{C}$ where $C1$ is any capacity added in parallel with the crystal. The placing of the frequency of infinite attenuation will depend upon the ratio $\frac{C2}{C1 + C_o}$. These ratios hold in each of the three cases, the element values being modified as shown on the diagrams.

If the maximum control over bandwidth and the placing of the attenuation frequency is to be obtained, the ratio $\frac{C_o}{C}$ should be low, a value of 250 having been found feasible for the range 5 to 8 Mc/s. However with FT243 types, it is likely to have a much higher value than this, since the crystals were designed for good frequency control characteristics rather than h.f. filter applications.

The formulae relating to the design of these filters are quite simple, and can be easily applied, but they require a knowledge of the values of the elements of the crystals. In the case of surplus crystals, these obviously are not known. Measurements can be made if suitable apparatus is available, and a method of carrying out these is described later. With a knowledge of the approximate values of the various components it is, however, possible to adjust the filter experimentally.

Lowpass Filter

After some initial calculations to determine approximate component values, the experimental approach was adopted with a single section of a lowpass filter, using an FT243 type crystal, whose resonant frequency was 8150 kc/s. The parallel capacitance of these units is high, in this case 13 pF and so no additional parallel capacity was required.

Small trimmers were used for $C1$ and $C2$, and the circuit arranged as shown in Fig. 15. The impedance of the filter depends upon the bandwidth and the crystal series capacity, but in general will be low, between a few hundred ohms and 5K ohms. The resistor T-network is to enable the signal generator to be isolated from the input of the filter. The output was fed via a pi-network to match the impedance to a receiver fitted with an S-meter. The voltage divider action reduced the input to the receiver and in some cases it may be desirable to use a cathode-follower instead of the resistive network. The filter would then be terminated by a 1·2K ohms resistor.

From this single section an attenuation of about 10-15db was obtained in the stopband, but minor passbands appeared due to the spurious responses and here the attenuation dropped to virtually zero. The rejection notch immediately h.f. of the passband was very deep and sharp. As a result it

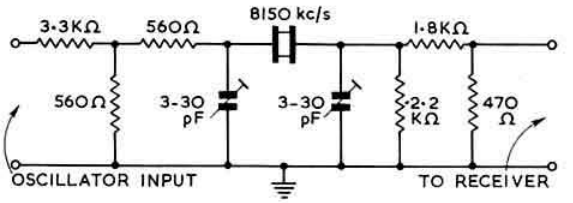

Fig. 15. Experimental single section of lowpass ladder filter using FT243 crystal.

would provide a high degree of suppression for any signal placed at that frequency such as a carrier. The disadvantage, as was expected, was the narrow bandwidth available due to the high parallel capacity of the crystal. The bandwidth was of the order of 1·5 kc/s and so would not be suitable for the generation of s.s.b.

Highpass Filter

A similar highpass filter was built using the same crystal, but results were not so good as for the lowpass version. The input and output impedances will be generally slightly higher and the maximum attenuation is very dependent upon the series resistance of the crystal at resonance. The passband was very narrow with the spurious responses providing alternate stop and passbands higher in frequency.

Conclusions on Ladder Filters

It would seem that the highpass filter is likely to be more critical than the lowpass version as regards requiring a low series resistance crystal, inferring of course a high Q factor.

In either case, a lower value of parallel capacity than that provided by the FT243 crystals would be most desirable. The variation of the parallel capacity between crystals of different frequencies is quite wide and does not show any definite trend. As a result it may be found that crystals of the same frequency have different values of parallel capacitance and if so, those with low values would be selected for use in filters.

It should be possible to overcome this disadvantage of narrow bandwidths by placing an inductor in parallel with each crystal. This reduces the effective parallel capacitance and so increases the pole-zero spacing. The value of inductance required depends upon the initial parallel capacitance of the crystal and the factor by which it must be reduced to enable the desired passband width to be achieved. The effective circuit below the resonant frequency of the crystal can be considered to consist of only the crystal parallel capacitance C_o and the added inductance L_o. Consequently, the susceptance of this combination is $2\pi fC_o \left[1 - \frac{f\infty^2}{f^2}\right]$ where $f\infty$ is the parallel resonant frequency of L_o and C_o. The effective value of C_o can now be reduced to any selected figure by the appropriate choice of $f\infty$ and hence L_o. The inductor should, if possible, be made variable to enable the passband to be adjusted easily after the filter has been built. This was not tried with the two sections described above, but should enable the FT243 type of crystal to provide sufficient bandwidth for s.s.b. transmitters and receivers.

The type of crystal which is cut especially for overtone operation will generally have a low parallel capacity at its fundamental frequency to enable the effective parallel capacity at the overtone frequency to be kept low. As a result, these crystals will make good filter crystals on their fundamental frequencies, but of course the overtone frequency may not be an exact multiple of the fundamental frequency. This is because the overtone is due to a mechanical rather than an electrical harmonic and so the effective element values may produce a slightly different output frequency to the electrical harmonic. It is therefore necessary to measure the fundamental frequency carefully.

Further information on ladder filters, their design and matching can be obtained from the monograph mentioned in reference [2].

Measurements

Measurements of the inductance, capacitance and resistance of a crystal cannot be made directly, but have to be deduced from measurements of the significant frequencies. The instruments required for this purpose are an oscillator covering the desired range and fitted with a fine tuning control, a valve millivoltmeter and an accurate frequency measuring device.

The oscillator should produce several volts output at a low impedance and this output should be reasonably constant over a range of ± 10 kc/s about the approximate frequency of the crystal to be measured.

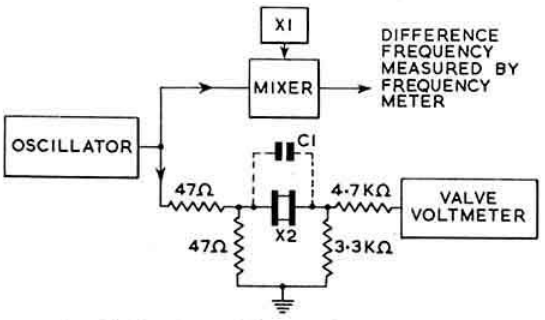

Fig. 16. Circuit used for crystal measurements.

The valve millivoltmeter is only required to indicate the changes in voltage as the oscillator is varied through the resonant and antiresonant frequencies of the crystal, and so can be of quite simple design. A broadly tuned r.f. stage in front of a normal valve voltmeter should be sufficient to give a workable deflection. Alternatively a receiver having a broad i.f. bandwidth and fitted with an S-meter could also be used.

Since quite small frequency changes must be measured, the best method is as illustrated in Fig. 16. The signal from the oscillator is fed to the crystal test circuit and also into a mixer. The other input to the mixer is from a crystal, X1, whose frequency differs from that of the crystal under test (X2) by something of the order of 250 kc/s to 1 Mc/s. The output of the mixer is broadly tunable over this range and so the difference frequency can be measured by comparison with a BC221 or similar frequency meter. The oscillation frequency of X1 is measured in the normal manner, as accurately as possible, although within limits this measurement does not govern the accuracy of the final results.

The oscillator is now tuned to the resonant frequency of X2 (where a maximum is indicated on the valve voltmeter) and the beat frequency from the mixer is measured, using the frequency meter. If the two frequencies X1 and X2 only differ by a small amount, a calibrated audio frequency oscillator can be used in place of the frequency meter. The anti-resonant frequency is found in a similar manner, where the valve voltmeter indicates the first minimum higher in frequency than the series resonant frequency. A small capacitor whose value is known (say 10 to 20 pF), is placed in parallel with the crystal and the new antiresonant frequency is determined. The actual frequency in each case is the oscillating frequency of X1 plus the difference as measured by the frequency meter. This assumes X1 is lower in frequency than X2. If the reverse is true, then the small difference frequency should be subtracted from the oscillating frequency of X1.

If the resonant frequency is fr, the antiresonant frequency fa, and the antiresonant frequency when the crystal is shunted by capacitor $C1$ is f_1, then C_0 can be found as follows:

$$C_0 = C1 \left[\frac{f_1^2 - fr^2}{fa^2 - f_1^2}\right]$$

where C_0 and $C1$ are in picofarads, and the frequencies are in megacycles per second. This value of C_0 includes any stray capacitance introduced by the measuring circuit, although the resistive network in Fig. 16 is designed to reduce stray capacitance due to the measuring instruments.

The equivalent series capacity is next found using the following relationship:—

$$C = C_0 \left[\frac{fa^2 - fr^2}{fr^2}\right]$$

where C and C_0 are in picofarads and the frequencies in megacycles per second.

The approximate formula,

$$C \simeq \frac{2.C_0.S}{fr.\ 10^6}$$

can be used, the pole-zero spacing S being in cycles per second while fr and the capacitances are in the same units as before.

From this result and the normal equation for a resonant circuit, the inductance in henries of the crystal (L) can be determined:

$$L = \frac{1}{4\pi^2 fr^2 C} \text{ henries}$$

where fr is in megacycles per second and C is in picofarads.

(concluded on page 392)

Onlookers at the Opening Ceremony which was broadcast in sound by the B.B.C. and filmed for television. *(Photo by John Miles, Falmouth)*

beam loaned by J-Beam Aerials Ltd. and a Marconi-built Army mobile s.s.b. station. G3OCB lent his home-built receiver and G3BHC a transmitter.

Considerable publicity was given to the Memorial Station by B.B.C. Television and Westward Television and the opening ceremony was broadcast in sound by the B.B.C.'s home and overseas services.

The operation reflects great credit on all members of the Cornish Radio and Telvision Club. Behind the scenes workers included G2BHW, G2DDR, G3NKE, G3NUJ, G3NVJ, G6LV and many others. The operators were G2JL, G2BHW, G3XC, G3AET, G3CZZ, G3DCJ, G3DLH, G3HES, G3HZV, G3IGV, G3MFW, G3MSU, G3OGT, G3OHM, G3OJN, G3OYW, G3PEP and G8AW. The overall operation was under the leadership of John Watson (G3AET), Chairman of the Club.

Thanks are due to Mr. Boaz, Falmouth Depot Manager of Marconi's Wireless Telegraph Co. Ltd. for his willing co-operation, the War Office, the Directors and Manageress (Mrs. Shoesmith) of the Poldhu Hotel and the National Trust.

A film of the event was made by G3OUZ and together with a tape recorded commentary will be available on loan to clubs and groups in return for a donation to the Cheshire Homes.

An Introduction to Crystal Filters (Continued from page 383)

If desired, the equivalent series resistance of the crystal can be found quite easily by noting the reading on the valve voltmeter at the resonant frequency and then replacing the crystal by known values of resistance until the same reading is obtained. The value of resistance giving the same reading is the value of the equivalent series resistance. Values ranging from a few hundred ohms to several kilohms will be found with normal crystals. In general, the lower the series resistance then the higher is the Q and so the more active is the crystal.

The frequency and amplitude of the spurious responses can be measured using the same method, and hence a full picture of each crystal can be obtained. This enables each crystal to be placed in the position where it will be most useful.

Conclusion

The subject of crystal filters is highly complex and obviously cannot be fully covered in an article of this nature. Further practical difficulties are encountered in the lack of suitable crystals and this undoubtedly hampers experiments in the field of high frequency filters. It is hoped, however, that this simplified treatment will serve as an introduction to the subject as a whole and so possibly provide a foundation on which further knowledge and experiment can be based.

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[1] Starr, A. T., " Electric Circuits and Wave Filters " App. IX p. 451 (Pitman).

[2] Sykes, R. A., " A New approach to the design of high frequency crystal filters " (Bell System Monograph 3180).

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Kosowsky, D. I., "The Synthesis and Realization of Crystal Filters " (Technical Report 298, June 1955, Research Laboratory of Electronics, M.I.T.)

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" *Single Sideband for the Radio Amateur*," A.R.R.L.

Modernizing the R.C.A.—AR88 Receiver (Continued from page 390)

(ix) Re-check all adjustments so that flat-topped response curves are obtained on positions 2, 3 and 4.

It should be noted that the response curve of a half-lattice filter is affected by the Q of the associated coils, especially the loading coils (T4 and Tb). The original T4 should be about right but it may be necessary to experiment with Tb in order to get the best results. If there is a deep trough in the middle of the response curve on position 2, which cannot be removed by careful trimming, then the L/C ratio of Tb is too low and a different one should be tried. It is, in fact, desirable to select Tb to tune with 100 pF or less, so that the response curve on position 2 is slightly rounded.

Steeper sides to the response curve may be obtained by using a little neutralization across each h.f. crystal. This device, however, has the disadvantage of producing side lobes to the response curve (caused by the unbalancing effect on the circuit) and is, therefore, not recommended especially as the sides of the response with all three filters switched in are already so steep that the slight improvement obtainable by using neutralization would scarcely be noticed.